The Individual Contribution of Automotive Components to Vehicle Fuel Consumption

by

Parhys L. Napier

Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

Fuel consumption has grown to become a major point of interest as oil reserves are depleted. The purpose of this study is to determine the key components that cause variation in the instantaneous fuel consumption of vehicles and their level of impact using an in-depth literature review of technical papers. The literature is rigorously screened using an algorithm that excluded unreliable studies by criteria defined herein. Papers that are identified using this strategy are stratified according to vehicle subsystem and component.

Relationships are established between external factors and fuel consumption using linear regression models and ranked by level of importance. Results show that coolant, air conditioning, alternator, rolling resistance and lubricants have an impact on vehicle fuel consumption and its variation. More specifically, coolant flow rate, oil viscosity, ambient temperature and tire pressure are found to be significant factors to fuel economy for the automobile.

Thesis Supervisor: John A. Ochsendorf

Title: Associate Professor of Civil and Environmental Engineering and Architecture

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1. Introduction

Vehicle fuel consumption has become a primary focus of the automotive industry in the last few decades. With the steady decrease in global oil reserves, more attention to greenhouse gas emissions and subsequent increases in gas prices, there is a need to address the eventual decline in fossil fuel availability. One approach to this problem has been to focus on the automobile itself. When fuel is put into a vehicle, it is used to power more than just the engine. From the engine to the headlights, fuel is used to power a multitude of components of the standard vehicle. By altering the design of a car, one can essentially change how much energy its different components will need, which in turn has an impact on the vehicle's fuel economy.

In order to better understand how a vehicle's design relates to fuel consumption, one must first understand how fuel powers the different components within a vehicle. Figure 1.1 shows the distribution of energy of a hypothetical midsized passenger, gasoline engine car. Although 100% of the fuel is put into the car, the energy derived from this fuel is spread throughout the car to power its different components.

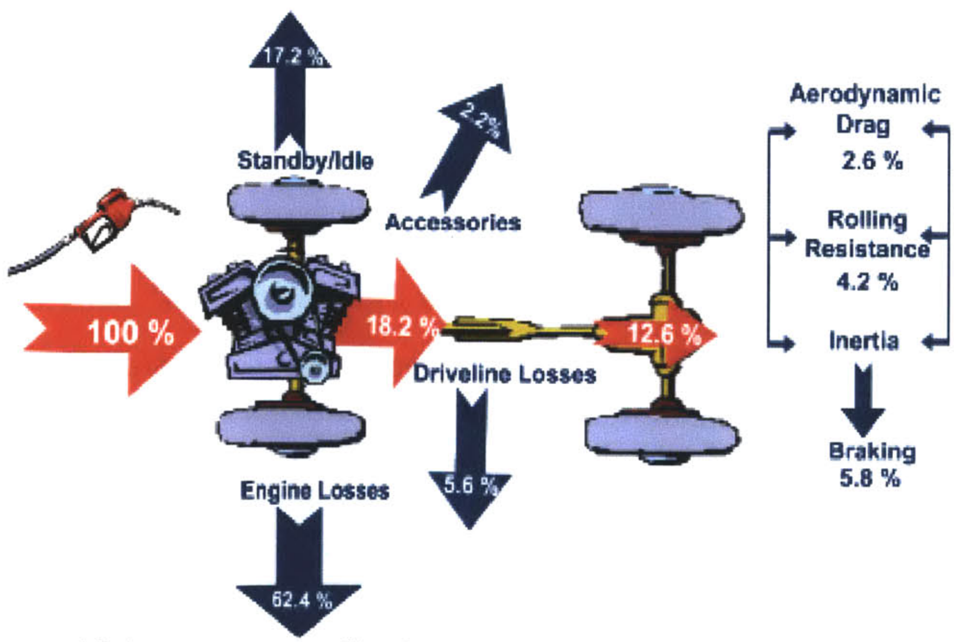

Figure 1.1 – Vehicle Energy Distribution for Hypothetical Gasoline Engine, Midsized Passenger Car [1]

This energy distribution is not the same for all vehicles or for all driving cycles nor is it the same for every vehicle of a particular class. Figure 1.2 demonstrates the vehicle energy distribution for a conventional midsized passenger vehicle.

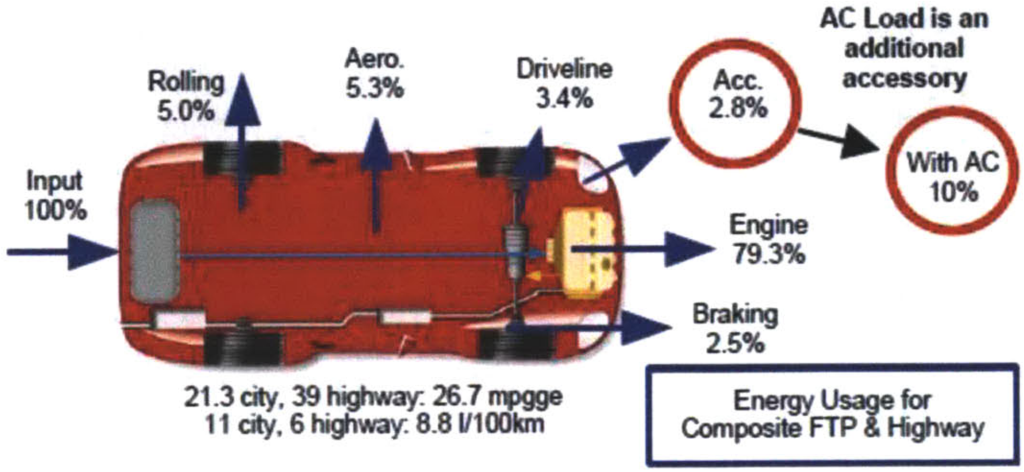

Figure 1.2 – Vehicle Energy Distribution for a Conventional 26.7-mpg Midsized Passenger Vehicle [2]

A Nissan Altima does not distribute energy the same way a Toyota Camry or a Chevrolet Malibu does due to differences in overall design and energy demands, despite all three cars being classified as midsized passenger vehicles. Despite this variation, Figures 1.1 and 1.2 bring attention to the fact that energy is distributed within a vehicle in specific ways. Percentages in consumption change across vehicles in key areas: engine, driveline, rolling resistance, aerodynamic drag, braking/inertia, standby/idle, and accessories. In a broader sense, these areas can be classified into three main subsystems of vehicle fuel consumption: the braking system, the electrical system and the powertrain.

Inconsistencies in the demands of these subsystems across the wide spectrum of automotives make it impossible to use values from any published vehicle energy distribution, such as Figures 1.1 and 1.2, as a model for all vehicles. Instead, each subsystem and its components has to be examined individually for a variety of vehicles and driving cycles to get a true sense of a component's fuel consumption in comparison to both other components' and to total vehicle fuel consumption.

The purpose of this study is to identify the key components responsible for vehicle fuel consumption and to determine how external factors influence fuel consumption for each component. Existing research studies typically focus on a specific component of the car, its lone effect on fuel consumption, and what factors control its energy consumption. This study identifies components that contribute to fuel consumption and variables that affect them in order to understand the role that vehicle-independent factors have on overall fuel consumption. In particular, attention is paid to the effect of ambient temperature on the various components investigated in this paper. Current research has shown that temperature may affect many individual components, making the total effect of ambient temperature a topic of interest in this study.

Once it is established which components affect energy consumption, an in-depth literature review is used to ascertain which external factors are key determinants of fuel consumption for each component. Data from select studies are used to establish quantitative relationships between vehicle consumption and external factors, and these are compared and ranked using defined criteria herein.

2. Methodology

This study employs an in-depth literature review to both identify and understand relationships between external factors and components as they pertain to fuel consumption of midsized, gasoline engine passenger cars. Due to the numerous papers available on this topic, a two-level filter is used to identify papers that are relevant to the goals of this study.

After correctly identifying the research that is most relevant to this study, the data provided is used to understand and establish meaningful quantitative relationships that are compiled into a single graph for comparison.

2.1. Filtering

Data is first filtered on the basis of reliability, with a detailed criteria of reliability provided in Section 2.1.1. After the study is found reliable, filtering is done by relevance to components of interest.

2.1.1. Study Reliability

Research is considered reliable if it meets the criteria listed below.

Publication date – due to significant technological advances with automotive components, no published works are used before 1990.

Published work – the study must be a published work that can be documented, preferably in a peer-reviewed journal. The study must also be published by an authority on automotives and/or research, such as the Society of Automotive Engineers (SAE), The Goodyear Tire & Rubber Company, an accredited research university, etc.

Uncertainty – there should be an error range in all calculations given that there should be uncertainty in the instruments used for measuring data.

Validity of data – detailed explanation, references and/or calculations must be given to explain any data – number, chart or graph – in the study in appendices or supplementary material.

2.1.2. Component Selection

From Figures 1.1 and 1.2, it is determined that the three subsystems of the vehicle that consume fuel are the braking system, the electrical system and the powertrain. Components that make up these subsystems are chosen for investigation by the number of papers that are found investigating a component's fuel consumption. Components with too few research papers on the topic – less than ten – are not investigated due to a lack of diversity in sources.

Only the electrical system and powertrain of midsized passenger cars are investigated for this study. The braking system did not have enough research available to perform a literature review and is therefore outside the scope of this study.

- *Electrical system* – air conditioning, alternator and battery;
- *Powertrain* – coolant, engine, lubricants, and tires;

Lubricants and coolant are not considered parts of the powertrain but are necessary for the operation of the engine, and each has numerous papers evaluating their relationships to vehicle fuel consumption. Thus, both are considered for this study.

2.1.3. Literature Review

An in-depth literature review of selected research is used to determine which external factors to explore for this study. A factor is required to be consistently explored as contributing to fuel consumption if at least 50% of the papers focused on a specific component. The literature review identifies eleven component-specific factors that influence fuel consumption for each vehicle component, which are listed below.

- *Air conditioning* – ambient temperature, relative humidity, and thermal comfort;
- *Alternator* – efficiency and electrical drag;
- *Battery* – ambient temperature, maximum voltage, and state of charge;
- *Coolant* – ambient temperature, coolant flow rate, material properties, and heat exchanger configuration;
- *Engine* – ambient temperature, engine type, friction, and size;
- *Lubricants* – viscosity and oil temperature;

- *Tires* – climate, coefficient of rolling resistance, tire pressure, tire wear and gross vehicle weight;

2.2 Establishing Relationships

The relationship between each external factor and its corresponding fuel consumption is investigated using a second set of criteria. All data is converted to the metric system for consistency. The data is analyzed using regression modeling to find direct correlations between fuel consumption and each external factor. These correlations are then compared and factors are ranked using specified criteria herein.

2.2.1. Normalizing Data

Papers used for this study are required to have data that is either in or able to be converted to a specified unit for the appropriate quantity measured.

- *Distance* – assessed in kilometers [km];
- *Energy* – assessed in kilojoules [kJ];
- *Fuel consumption* – assessed in liters per 100 kilometers traveled [L/100 km];
- *Mass* – assessed in grams [g];
- *Power* – assessed in kilowatts [kW];
- *Pressure* – assessed in kilopascals [kPa];
- *Speed* – assessed in meters per second [m/s];
- *Temperature* – assessed in degrees Celsius [°C];
- *Time* – assessed in seconds [s];
- *Volume* – assessed in liters [L];

In papers where data is not provided in the above units, all necessary conversions are made using Table 2.1 to have comparable data.

Table 2.1 – Conversion Table

Unit Conversion Table				
Measurement	**Unit**	**Conversion Factor**		
Distance	km	1000 m	3281 ft	0.62 mi
Energy	kJ	1000 J	0.9478 btu	2.778×10^{-4} kWh
Mass	g	0.001 kg	---	---
Power	kW	1000 W	1.341 hp	---
Pressure	kPa	1000 Pa	0.145 psi	---
Speed	m/s	3.281 ft/s	2.237 mph	---
Temperature	°C	([°F] - 32) x 5/9	[K] – 273.15	---
Time	s	2.778×10^{-4} hr	---	---
Volume	L	0.2642 gal	---	---

2.2.2. Regression Modeling

Linear relationships are searched for in order to understand the effect of a particular factor on variability in vehicle fuel consumption. Data is collected from selected studies and analyzed using Microsoft Excel regression analysis to discern if a relationship exists and its strength. The criteria below are used to understand the relationship between variables.

Coefficient of determination – linear regression models with a high coefficient of determination (R^2) indicate a strong relationship between the independent variable, i.e. contributing factor, and dependent variable, i.e. the corresponding component's fuel consumption. For this study, a relationship is considered weak if the coefficient of determination is less than 0.5.

Slope – the slope of a line indicates the effect a unit change in the external factor has on the fuel consumption. The magnitude of the slope indicates the impact of the external factor.

Statistical significance – findings from a study are required to be statistically significant at a confidence interval of 90% or higher.

2.2.3. Significant Consumption

After quantifying the relationship between each factor and vehicle fuel consumption, it is necessary to establish if the relationship is significant in comparison to other factors. Significant consumption is defined using the following criteria.

Order of magnitude – numerical comparison for significance is done by comparing orders of magnitude. A number is considered insignificant if it is two or more orders smaller than the number it is compared to (i.e. at least 100 times smaller).

Slope comparison – direct comparison between fuel consumptions is used for ranking. Top rank is given to the factor that has the largest slope magnitude in its linear regression model.

In cases where a paper only provides data in the form of numbers and/or charts, direct quantity comparison is the only method used for determining significant consumption.

Using this two-step methodology, this study is able to focus directly on current research useful to this study and provides a concise way to identify and quantify relationships between external factors and fuel consumption. These eleven relationships are compiled into a table and graph for comparable analysis at the end of the study.

3. Automobile Components

In order to establish relationships between external factors and fuel consumption, it is important to first investigate and understand why the factor has an impact at all. The major variables discovered in the literature review are explored to provide an overview of what each component does, how the identified external factors are related to the component, and how that relationship results in fuel consumption for the car.

3.1. Electrical System

Cars use an extensive electrical system to produce, store and distribute all electricity needed to run smoothly and offer the driver comfort during travel. This electrical demand comes from the many components that depend on electricity for operation and is met by means of fuel consumption. The components within the electrical system that contribute to this consumption and are explored in this study include the air conditioning, alternator, and battery.

3.1.1. Air Conditioning

The automotive industry as a whole has stated that the air conditioning system contributes greatly to a vehicle's fuel consumption (Figure 3.1). More specifically, a large percentage of the electrical demand of a car can be attributed to the air compressor. Depending on the type of car and size, this percentage varies, though it is consistently found to be highest for hybrid electric vehicles [3].

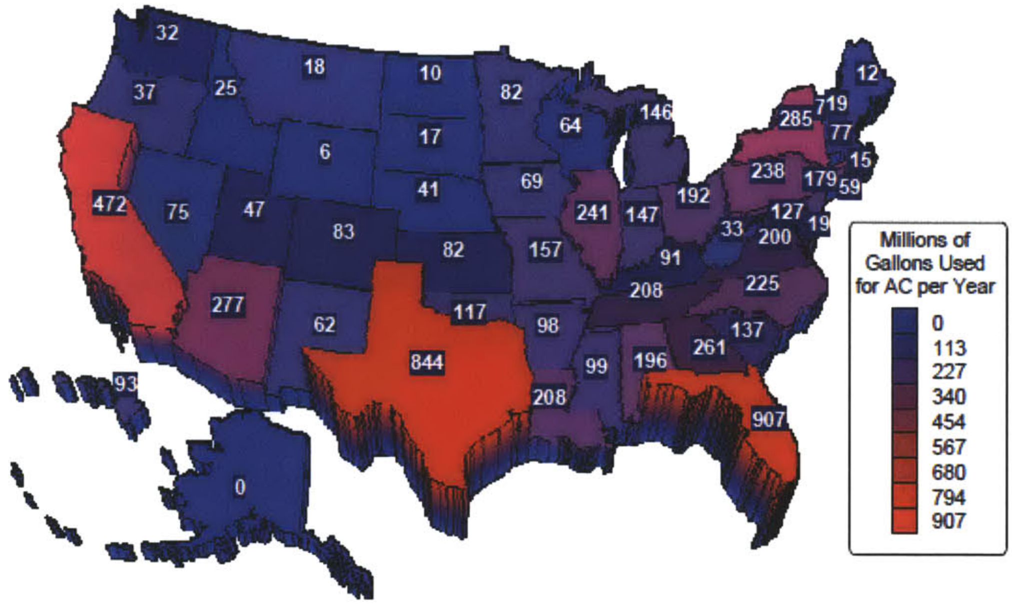

Figure 3.1 – Fuel Consumption from Air Conditioning Use by State [2]

Given the large variety of vehicles that exist, this study focuses on factors independent of the automobile that influence air conditioning electrical demand during steady-state operation [2-5]: ambient temperature, relative humidity and thermal comfort.

Ambient temperature – the temperature outside of the vehicle is an indication of solar load and the need for air conditioning. Solar load refers to the solar intensity, in W/m^2, of the sun's radiation on the car's surface. The magnitude of this load influences thermal conditions in the car by means of conduction (through the frame and windows), convection (heating up circulating air inside the vehicle), and radiation (through the car and air).

Ambient temperature also indicates whether or not there is a need for air conditioning (AC). The purpose of the AC is to cool the cabin of the vehicle when there is thermal discomfort from heat – the converse would be the heater, which is used to heat the cabin when there is thermal discomfort from coldness. As Figure 3.2 indicates, the six top fuel consumers in the United States are historically known to be hot states, located in the southern United States or near the equator. These values are calculated from the values in Figure 3.1 and 2001 state motor vehicle registrations [6].

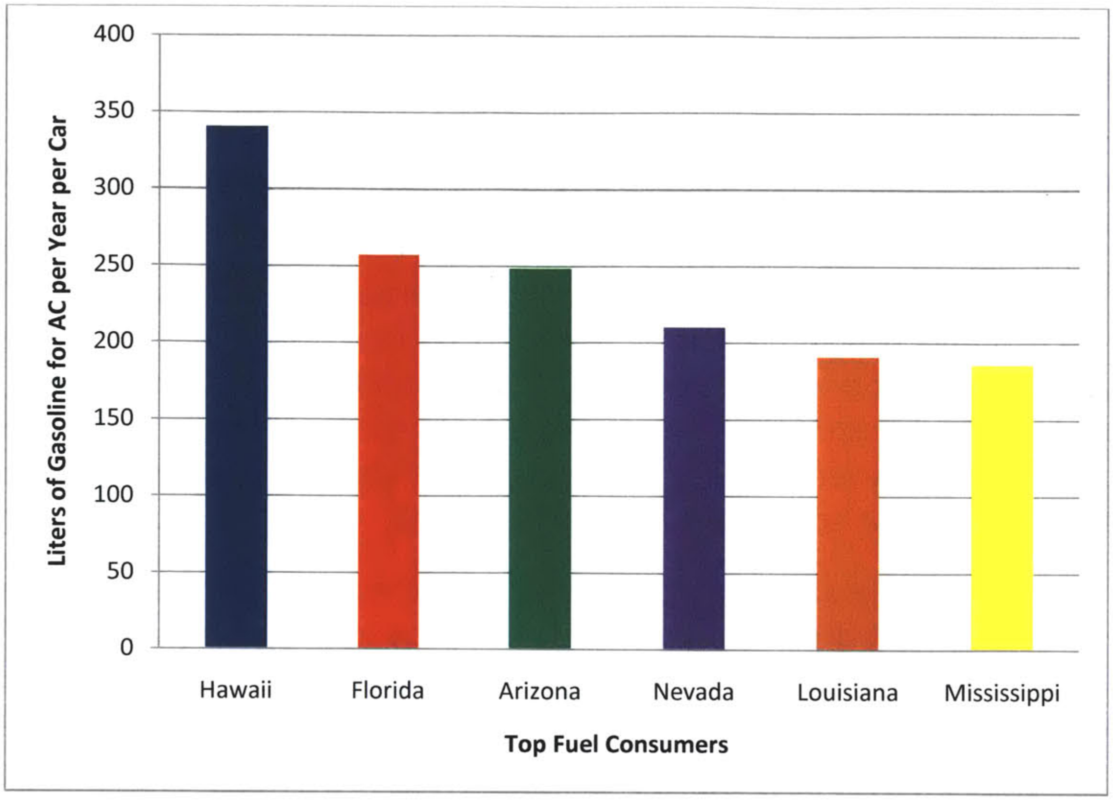

Figure 3.2 – Top Six Fuel Consumers in the United States in 2001

Relative humidity – relative humidity refers to the amount of water vapor in the air at a specific temperature compared to the maximum water vapor that the air is able to hold without it condensing, at that given temperature. The more humid the immediate environment, the greater the chance that a person will sweat, leading to discomfort and a need for air conditioning.

Thermal comfort – human thermal comfort is defined as the state of mind that expresses satisfaction with the surrounding environment and I maintained when the body maintains thermal equilibrium with the surroundings. Both ambient temperature and relative humidity contribute to an individual's thermal comfort as they help shape the conditions of the surrounding environment, i.e. preference for cold/hot weather, humidity that exacerbates sweating, etc. Due to the subjective nature of thermal comfort, however, it is not analyzed for this study.

3.1.2. Alternator

The automotive alternator works in conjunction with the battery to generate power for the electrical components of a vehicle while the engine is running, including the instrument panel and exterior and interior lights. It is also designed to charge the battery. The alternator works by producing AC power through electromagnetism.

A literature review of papers focusing on alternators consistently isolates two variables that directly affect alternator performance [7-11]: efficiency and electrical drag.

Efficiency – the efficiency of an automotive alternator is linked specifically to its design. Efficiency is a result of bearing loss, iron loss, copper loss, fan cooling loss, and the voltage drop in the diode bridges during operation. Depending on the size of the alternator and its speed, efficiency can reach up to 62% [7]. Efficiency is not a factor for this study, however, as the type of alternator is kept consistent in all calculations.

Electrical drag – the alternator puts drag on the engine when it is running as it pulls in energy in order to operate. The energy loss from this drag requires more fuel to be consumed in order to overcome it. From equation (1), the power loss from drag is defined as

$$\mathrm{P}_{drag} = \eta_{loss} \cdot I \cdot V_{battery} \tag{1}$$

where P_{drag} is the power loss from drag in kW, η_{loss} is the alternator's efficiency loss, I is the current draw in amps, and $V_{battery}$ is the initial battery voltage in volts. High electrical drag indicates more total energy use while driving. As alternator efficiency is kept constant for this study, it is apparent from (1) that current and maximum voltage affect electrical drag.

3.1.3. Battery

The battery is a rechargeable device designed to supply an automobile with electric energy. It serves as the power source for the electrical system and the engine.

A thorough literature review reveals that the battery itself has little direct impact on the fuel consumption of a vehicle during steady-state operation as its behavior does not change. As a source of energy, it is the components that draw power from the battery through the alternator that effect fuel consumption, not the battery itself. It is noted, however, that factors exist which affect the energy output of the battery [8-14].

Ambient temperature – chemical reactions inside of batteries take place more slowly when the battery is cold. The battery produces less current, providing the starter motor with less energy to draw from.

Maximum voltage – a battery's maximum voltage is a measure of its electric potential. Voltage can be interpreted as energy per unit charge, with higher maximum voltage indicating more potential energy output from the battery to other components of the car.

State of charge (SOC) – SOC is the equivalent of a fuel gauge for a battery. It is a ratio of the amount of energy available in a battery to the maximum energy it contains. The state of charge of the battery affects the initial voltage it can provide, and consequently, the maximum amount of energy that can be drawn.

3.2. Powertrain

The powertrain refers to the group of components that generate power and deliver it to the air, water and road surface. This power comes from the energy released from the combustion of gasoline inside the engine, and the amount of power needed depends on the demands of the components that require. The components within the powertrain that contribute to this consumption and are explored in this study include the coolant, engine, lubricants and tires.

3.2.1. Coolant

Coolant is used as part of the cooling system to prevent overheating of the engine. Gasoline engines are not efficient at turning chemical energy into mechanical power, causing most of the energy to be converted into excess heat. Four variables are identified as the main factors contributing to fuel consumption by the coolant [15-17]: ambient temperature, coolant flow rate, material properties and heat exchanger configuration.

Ambient temperature – Liquids get thicker in cold weather. Depending on the temperature of the environment and the liquid's heat capacity, the ambient temperature can alter the viscosity of the coolant.

Coolant flow rate – The speed of the coolant, as it moves through the heat exchanger, influences the liquid's effectiveness as a heat absorber by altering the type of flow – laminar, transient or turbulent.

Material properties – An ideal coolant has low viscosity, high thermal capacity, is non-toxic, low-cost, and chemically inert. Coolants vary in these properties, which influences the liquid's ability to transfer heat. Material properties, however, are not investigated for this study as only one type of coolant is investigated.

Heat exchanger configuration – Coolant is a heat transfer liquid that flows through the engine to absorb heat via heat exchanger. Depending on the design of the heat exchanger it is flowing through, the effectiveness of the cooling system can change. All studies kept consistent cross-flow heat exchanger configurations for testing, and consequently, this variable is not investigated for this study.

3.2.2. Engine

Internal combustion engines are designed to burn fuel to release stored energy. For gasoline engines, an oxidizer (air) converts gasoline into mechanical power by using the expansion of high-pressure and high-temperature gases produced by the combustion process to apply direct force to the engine's components. These components, such as the nozzle, pistons and turbine blades, generate mechanical energy that can be use to move an automobile.

From a literature review of relevant papers, it is found that four variables consistently affect fuel consumption from the engine [18-25]: ambient temperature, engine type, friction and size.

Ambient temperature – Low temperatures affect the engine's ability to function. Gasoline evaporates less in cold weather, making it more difficult to burn and produce energy. Chemical reactions happen slower in the battery in the cold, reducing the amount of available energy for the vehicle. Additionally, oils get thicker in cold weather, making it difficult for the engine to move around the coolant and lubricants running through it.

Engine type – Modern engines are typically gasoline, diesel or hybrid electric engines. Each engine type comes with its own variations in designs and efficiency, which alters how much fuel is consumed. In light of this, the focus of this study is put on gasoline engines only, so the effect of engine type is not investigated.

Friction – Components of the engine move and slide against each other while the engine is running. The engine experiences kinetic friction from this motion, which requires additional fuel to overcome. The relationship between friction and fuel consumption, however, is focused on more in the Lubricants section of this paper.

Size – Larger engines consume more gasoline. Energy is needed to move both the subcomponents of the engine and the vehicle load. This energy demand is higher if the engine is bigger due to the weight of the parts or if there is a need to provide higher performance, such as racing. However, as this study focuses only on midsize passenger cars, engines investigated in this study are generally of the same size, making it unnecessary to explore this aspect.

3.2.3. Lubricants

Friction is responsible for significant fuel consumption in vehicles (Figures 3.3 and 3.4). Use of the engine requires movement of several heavy components, such as pistons and the crankshaft, but friction between parts resists these movements. This friction is minimized by the introduction of oil lubricants. Thorough lubrication reduces kinetic friction during engine operation and, consequently, the amount of fuel consumed to overcome that friction.

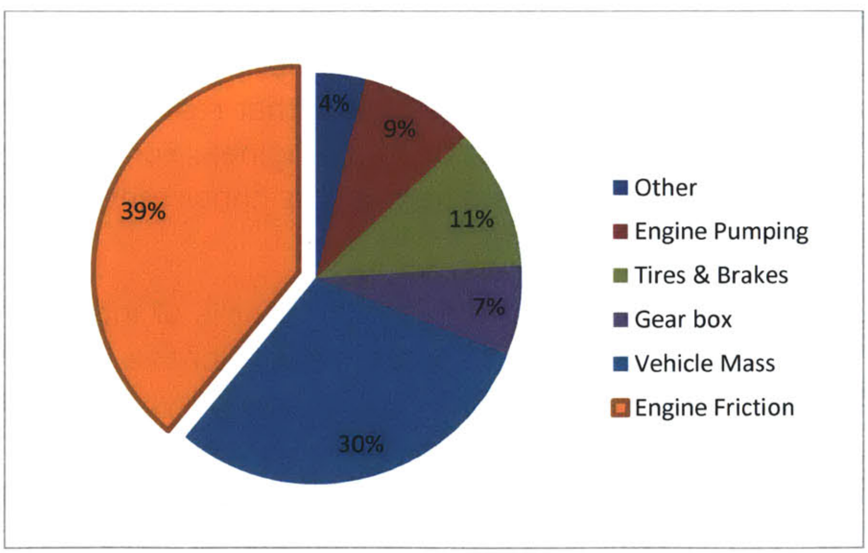

Figure 3.3 – Engine Energy Distribution for Gasoline Engine in Urban Driving Cycle at 20 °C [26]

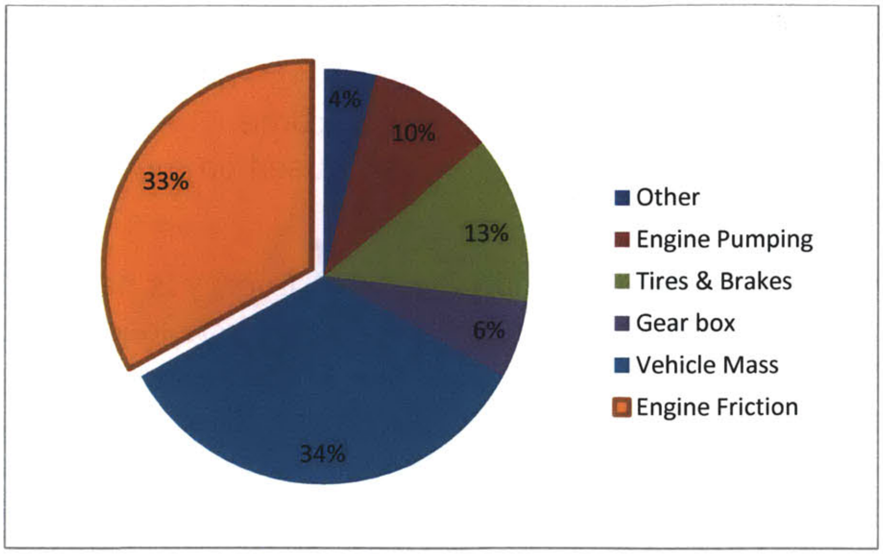

Figure 3.4 - Engine Energy Distribution for Gasoline Engine in Urban Driving Cycle at 90 °C [26]

Extensive research has been done on the correlation between lubricants and engine performance. A thorough literature review on technical papers relevant to the topic reveals that the two consistent contributors to lubrication effectiveness are viscosity and oil temperature [26-30].

High-temperature, high-shear (HTHS) oil (dynamic) viscosity – Viscosity is a measure of a fluid's internal friction, which is caused from individual layers of the substance sliding against each other. The greater a fluid's viscosity, the more resistant it is to movement and the more susceptible it is to shear flow. In particular, HTHS viscosity refers to a lubricant's viscosity under severe high temperature and shear conditions that resemble highly-loaded journal bearings in fired internal combustion engines. For the purpose of this study, this is the viscosity test examined as it is consistently used in all related technical papers [26-30].

Oil temperature – The temperature of the lubricant is of interest as it is indicative of two things – the specific heat capacity of the lubricant and the liquid's changing viscosity. Figure 3.5 depicts how oil viscosity decreases as temperature increases for a variety of SAE oil lubricant classes. Consequently, this variable is kept controlled in the papers that analyzed lubricant effects on fuel consumption, and there is no investigation on its effect on fuel consumption.

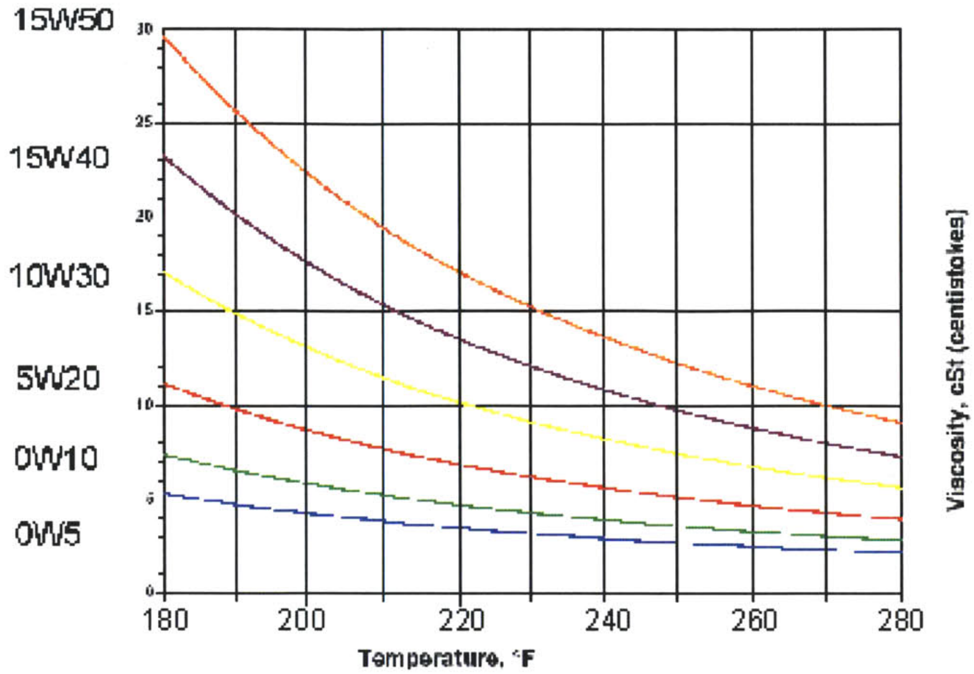

Figure 3.5 – Relationship between Oil Viscosity and Oil temperature [31]

3.2.4. Tires

The visco-elastic rubber compounds in tires undergo deformations, which affect how tires interact with the road. Energy is lost as the tires roll under load, and in order to overcome this loss of energy, the vehicle must consume additional fuel [32-33].

A literature review through papers focusing on the impact of tires on fuel economy consistently isolate four variables that directly affect a vehicle's fuel consumption [32-40]: climate, coefficient of rolling resistance, tire pressure, tire wear and gross vehicle weight.

Climate – Depending on environmental conditions, tires behave differently in different settings. In cold temperatures, rubber contracts and hardens; in hot temperatures, it expands and becomes more elastic. Dry weather removes moisture from the air and, consequently, the roads, making the roads rougher and increasing friction. Rain and snow make roads wet and slippery, decreasing friction with the tires. Temperature also affects the air inside the tire, increasing pressure in hot temperatures from expansion and decreasing in cold temperatures from contraction. Each weather condition changes the type of interaction that occurs between roads and tires while driving. These conditions can be split into two categories:

- Ambient temperature.
- Precipitation, which is outside the scope of the current study.

Coefficient of rolling resistance (C_{RR}) – the coefficient of rolling resistance is a ratio of the force that maintains contacts between the tires and the road and the frictional force that resists the motion of the vehicle (2). Coefficients of rolling resistance are typically measured on rollers, with power meters on road surfaces, or with low-speed coast-down tests where the effect of air resistance is subtracted.

$$C_{RR} = \frac{F_{RR}}{Mg} \tag{2}$$

A tire's C_{RR} is an indication of how much power is needed to move a vehicle on the road (rolling resistance), and more importantly, how much fuel the vehicle would consume in doing so. Tires with low coefficients of rolling resistance are considered to be fuel efficient as they require less energy for driving.

Tire pressure – the air in the tires of a vehicle behaves like a longitudinal spring within the tire walls (Figure 3.6).

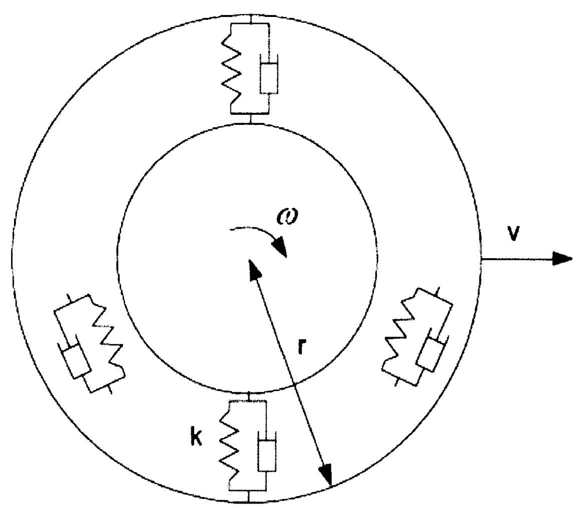

Figure 3.6 –Tire Pressure Mechanics [37]

Increasing the air pressure is equivalent to increasing the stiffness of a spring, and equally, low pressure in tires results in a loss of spring stiffness. This loss in longitudinal stiffness increases tire slip while driving, reducing traction and forcing the vehicle to consume more fuel to overcome this problem.

Tire wear – the tire's ability to grip the road decreases with wear due to the removal of rubber from the tire tread. That grip is needed to maximize friction between the car and the road and move the vehicle forward and without that friction, the engine burns more fuel in order to get the car to move. This variable, however, is not investigated for this study.

Gross vehicle weight – The weight of the vehicle directly impacts the load on the tires (3).

$$F_{RR} = C_{RR} \cdot M \cdot g \tag{3}$$

where F_{RR} is the load, M is the vehicle mass, and g is the acceleration of gravity (9.81 m/s^2). Vehicle mass is directly proportional to load, illustrating that an increase in mass should result in an increase in load, and therefore, requires more energy to overcome that resistance. This variable is not investigated for this study as all tire pressure for cars considered here are within the specified range for midsized passenger cars regulated by the EPA.

Investigating the contribution of each component and its corresponding external factors to vehicle fuel consumption gives insight into the complex, interrelated nature of vehicle fuel consumption. Several components are discovered to be directly or indirectly influenced by the same factors, namely ambient temperature. This emphasizes the need to explore individual relationships between each factor and fuel consumption in order to gauge a factor's impact.

4. Results and Summary

With an understanding of each vehicle component and the effects of external factors have on component fuel consumption, relationships between those factors and fuel consumption are explored. Data from select studies are used to develop linear regression models, and from these models, direct, quantitative relationships between factors and fuel consumption are established.

4.1. Electrical System

4.1.1. Air Conditioning

To calculate average vehicle fuel consumption per state from air conditioning use, the following relationship is used

$$\overline{FC}_{state} = \frac{F_{state}}{VMT_{state}} \tag{4}$$

where *F* is fuel in liters, *VMT* is vehicle-miles traveled in km, and *FC* is fuel consumption in L/100 km.

Data is pooled from several sources. Annual average ambient temperature and relative humidity for each state in 2001 is taken from the U.S. Department of Commerce, National Oceanic & Atmospheric Administration [41-42]. Total vehicle-miles traveled in 2001 are taken from the U.S. Department of Transportation, Federal Highway Administration [43]. Population by state is found using the 2000 U.S. Census Bureau [44] and data for the total fuel use for light-duty vehicle air conditioning by state is obtained through literature review [2] from Wards 2001 Automotive Yearbook.

Figure 4.1 shows a strong correlation between average annual ambient temperature and average fuel consumption, with a coefficient of determination equal to 0.556. The data is found to be statistically significant at a 95% confidence interval, and from its slope, indicates that a 1.0 ± 0.5 °C increase in ambient temperature results in approximately a 0.05 ± 0.01 L/100 km increase in fuel consumption.

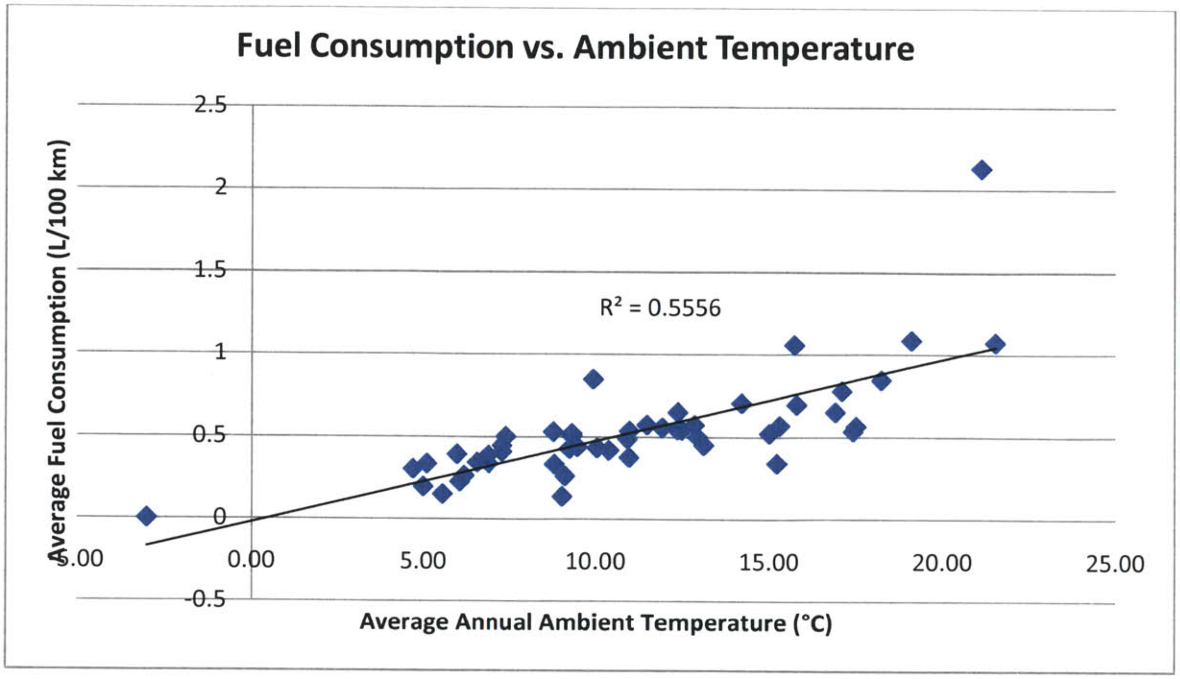

Figure 4.1 – Correlation between Fuel Consumption and Ambient Temperature for Air Conditioning

Figure 4.2 shows a poor correlation between average annual relative humidity and fuel consumption, with a coefficient of determination of R^2 = 0.007. The data is found to be statistically insignificant at a 95% confidence interval and indicates that there is little relationship between relative humidity and fuel consumption.

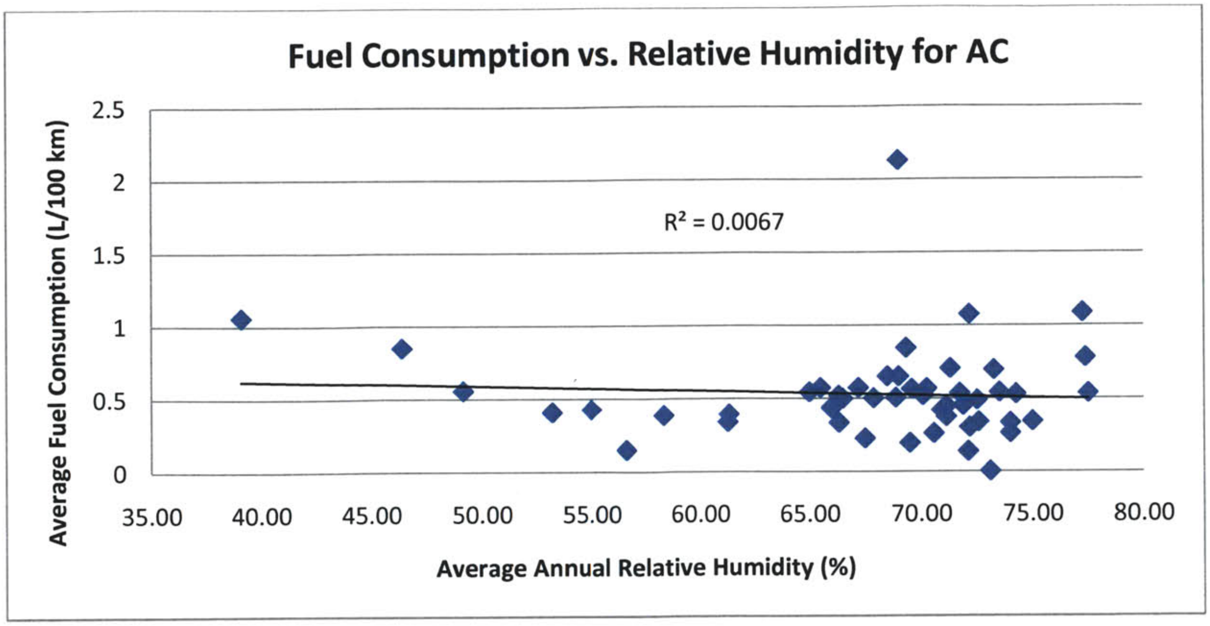

Figure 4.2 – Correlation between Fuel Consumption and Relative Humidity for Air Conditioning

4.1.2. Battery and Alternator

From equation (1), it is shown that the alternator depends heavily on battery performance. For that reason, both components are analyzed together in this section.

Data from study [13] is used for battery behavioral analysis, which investigates the Smart Electric Power Management as it pertains to vehicle charging. The vehicle battery, with an initial charge of 13.0 ± 0.5 V, is analyzed to determine the relationship of SOC and temperature with battery performance prior to charging.

From Figure 4.3, it is demonstrated that both temperature and SOC directly affect voltage output. The effect is greater at lower states of charge, where differences in voltage measurements between temperatures are larger.

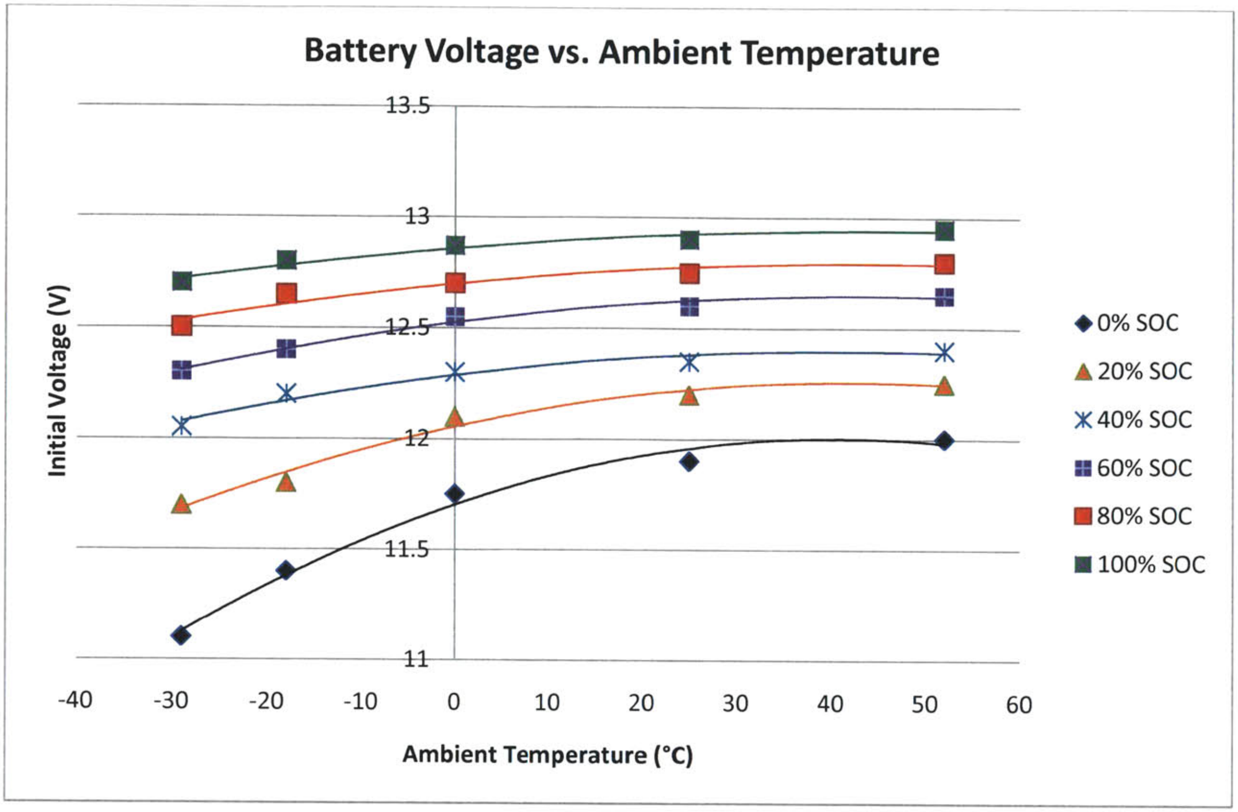

Figure 4.3 – Battery Behavior due to Ambient Temperature and SOC [13]

From Figure 4.3, low temperatures cause an exponential decay in battery voltage as SOC decreases, beginning at 25 °C that grows stronger at lower temperatures. For 25 °C and higher, the effect of ambient temperature is significantly smaller and voltage output reaches a maximum.

Polynomial regression lines predicting battery voltage from ambient temperature are derived for each SOC. These regression models are then used to predict alternator behavior at different states of charge and temperature. It is assumed that the alternator efficiency is 62%, the maximum battery voltage is 13.0 ± 0.5 V, and that the vehicle is moving at a speed of 80 km/hr.

In order to calculate the fuel consumption that come from using the alternator in conjunction with this battery, it is first necessary to determine how much power is needed for the alternator to operate as follows

$$P_{total} = P_{desired} + P_{drag} = I \cdot V_{battery} + \eta_{loss} \cdot I \cdot V_{battery} \tag{5}$$

$$P_{total} = (1 + \eta_{loss}) \cdot I \cdot V_{battery} \tag{6}$$

The total power draw from the alternator includes the electric drag incurred from efficiency loss. That power is converted to fuel consumption using equation 7

$$FC = P_{total} \cdot t_{100} \cdot \frac{1\,L}{34.8\,MJ} \cdot \frac{1}{100\,km} \tag{7}$$

where t_{100} is the time is takes to drive 100 km at 80 km/hr (4500 s) and 34.8 MJ is the amount of energy released from combusting 1 L of gasoline.

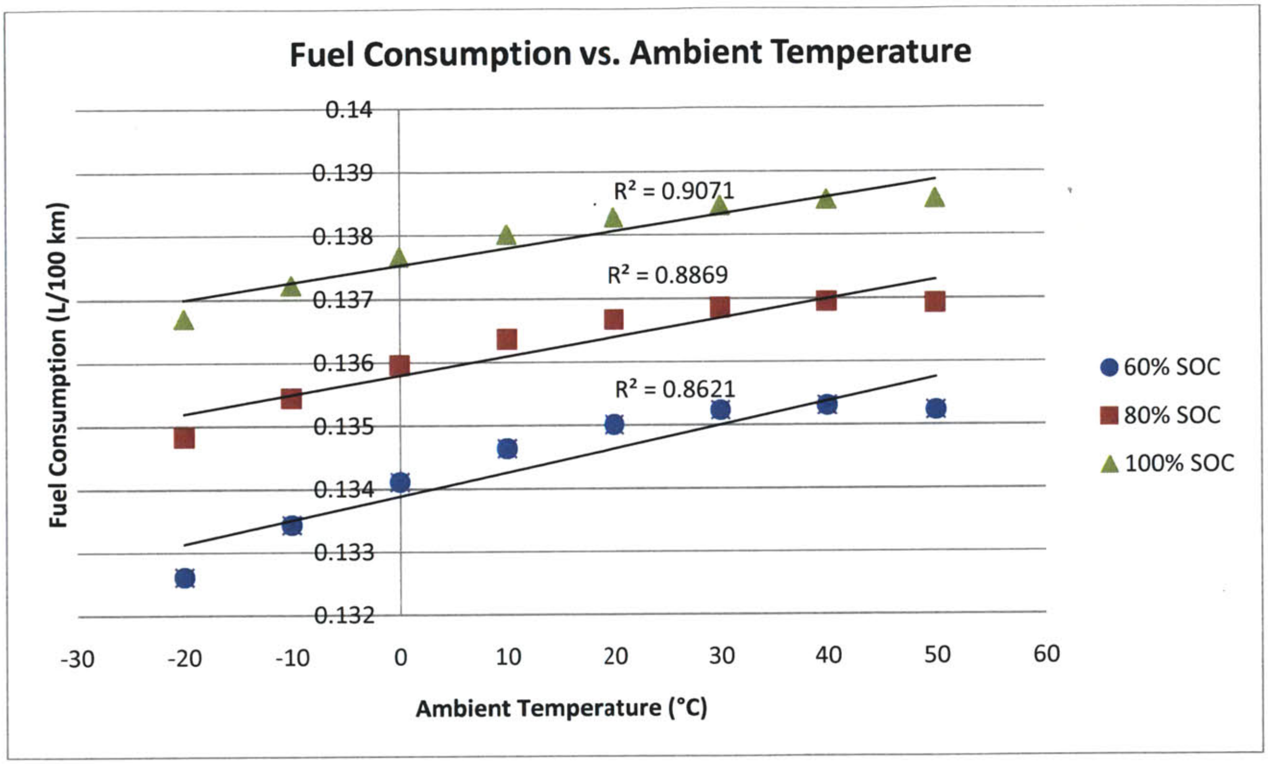

Figure 4.4 - Correlation between Fuel Consumption and Ambient Temperature for Alternator

Figure 4.4 models the effect of ambient temperature on the fuel consumption from an alternator with an arbitrary current output of 60 A. The relationship between the variables becomes increasingly linear as the SOC increases, with each model having a high R^2 value. For a SOC of 100%, it is determined that a 1.0 ± 0.5 °C increase in temperature results in a $3 \times 10^{-5} \pm 5 \times 10^{-6}$ L/100 km increase in fuel consumption. For an SOC of 60% and 80%, a 1.0 ± 0.5 °C increase in temperature results in a $4 \times 10^{-5} \pm 5 \times 10^{-6}$ L/100 km increase in fuel consumption, indicating that at a lower SOC, more fuel is consumed.

Figure 4.5 shows the relationship between alternator current output and fuel consumption for the battery at 100% SOC. The regression model is perfectly fitted to the data ($R^2 = 1$) as all of the data is hypothetical. It is important to note, however, that the slope of the line indicates a weak relationship between current output and fuel consumption. According to the figure, an increase of 1.0 ± 0.5 A in current output would result in an increase of 0.002 ± 5 x 10^{-4} L/100 km in fuel consumption for the alternator.

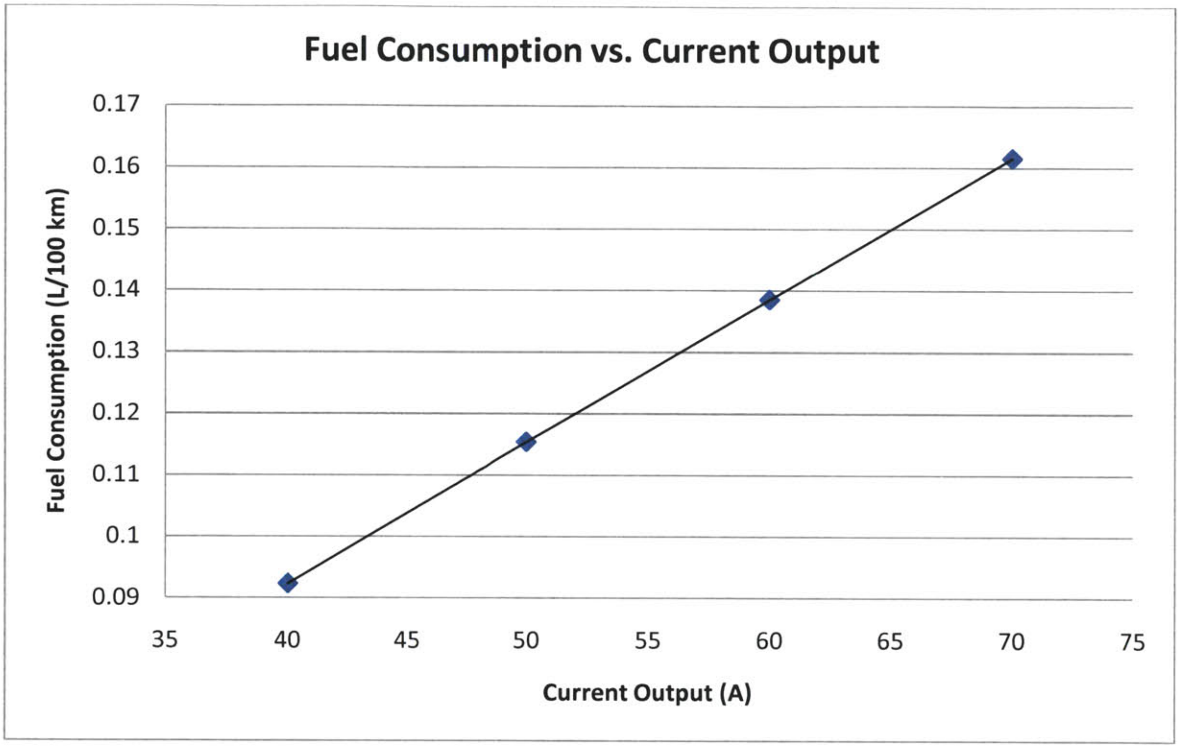

Figure 4.5 – Correlation between Fuel Consumption and Current Output for Alternator

For both Figures 4.4 and 4.5, all data is found to be statistically significant at 95% confidence interval.

4.2. Powertrain

4.2.1. Coolant

Several studies investigate the contribution of coolant to vehicle fuel consumption, and results are consistent across technical papers. Therefore the data from one study [17] is used to show the findings.

The study described in [17] is held in a Monash full-scale wind tunnel with a maximum wind velocity of 50 m/s. The coolant used is a glycol and water mixture in equal proportions. The maximum coolant temperature prior to testing is 70 °C, and the coolant flow rate is controlled by a valve and measured by a magnetic flow meter. Temperature is measured using T-type thermocouples and all measurements are recorded by a host computer through a Data Acquisition Unit.

For coolant, ambient temperature effects on specific dissipation are studied and analyzed. Results are shown at laminar (Figure 4.6), transitional (Figure 4.7) and turbulent (Figure 4.8) flows. All data is found to be statistically significant at 95% confidence interval.

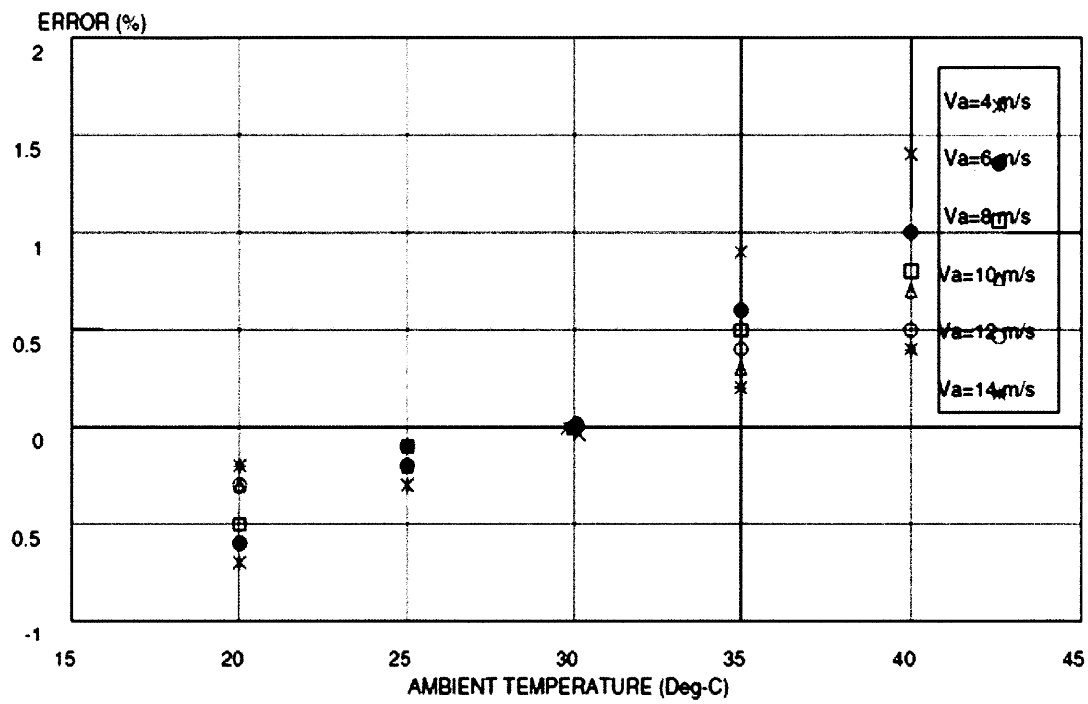

Figure 4.6 – Fuel Consumption Sensitivity to Ambient Temperature for Laminar Flow [17]

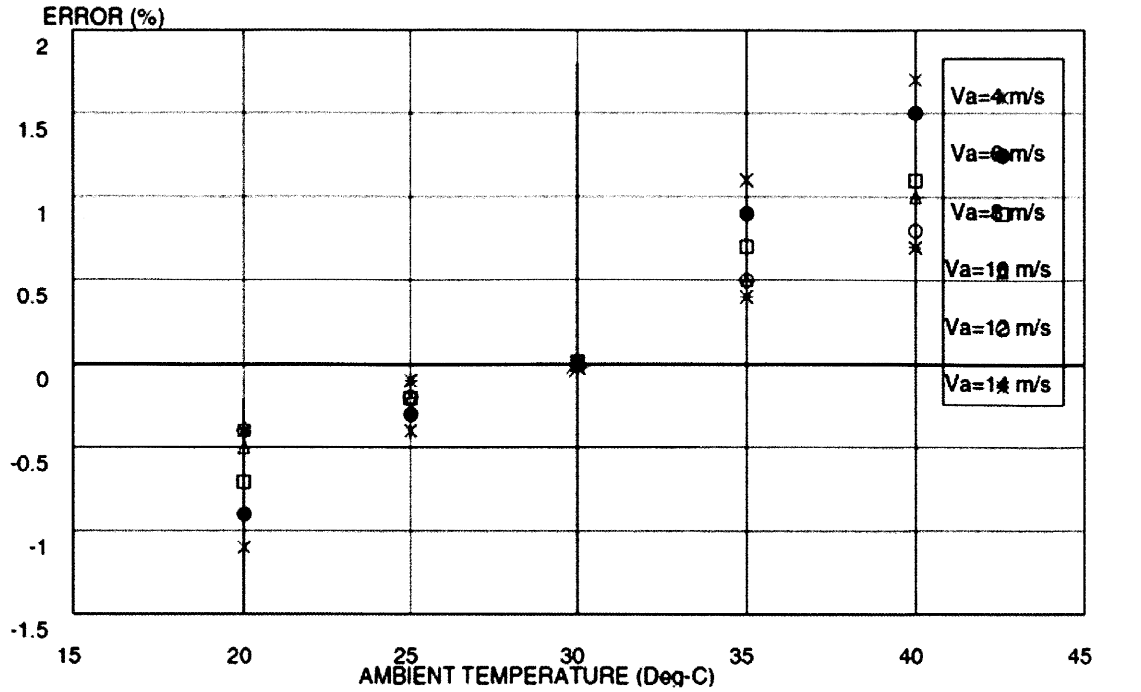

Figure 4.7 – Fuel Consumption Sensitivity to Ambient Temperature for Transient Flow [17]

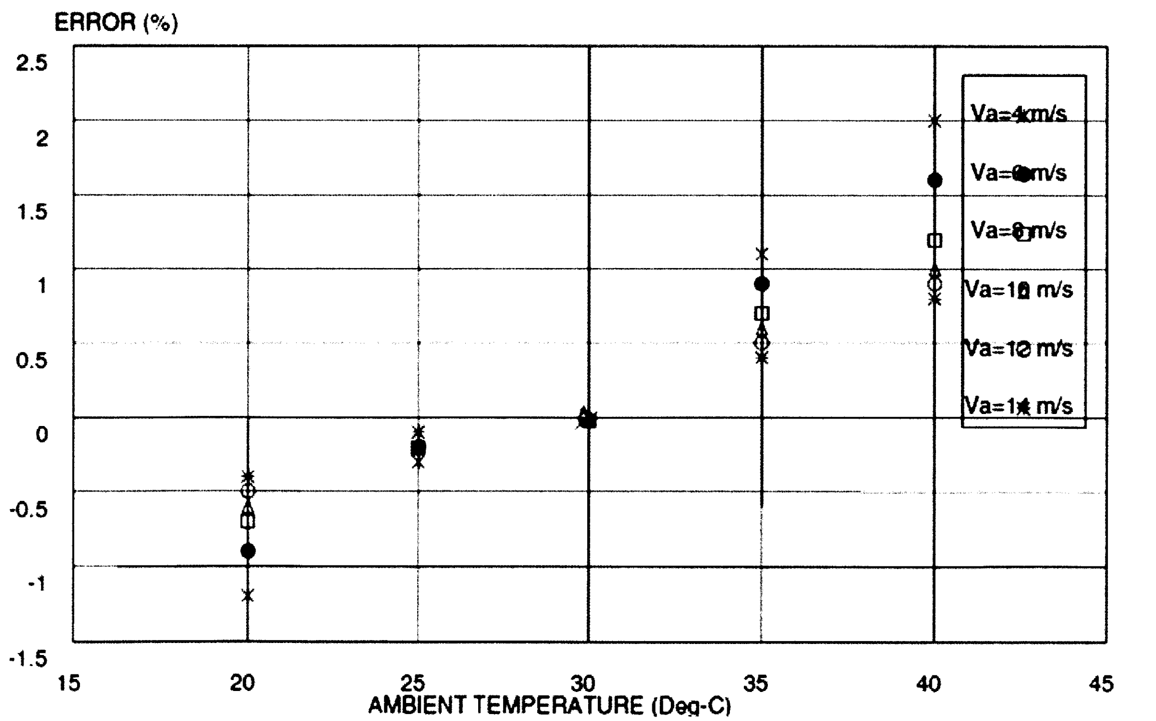

Figure 4.8 – Fuel Consumption Sensitivity to Ambient Temperature for Turbulent Flow [17]

Figures 4.6-4.8 depict specific dissipation sensitivity to ambient temperature. The percent error indicates the change in dissipation relative to results obtained at 30 °C. Errors are less than ±1.0% under laminar flow and less than ± 1.5% for transitional and turbulent flows for temperature variation within 10 °C [17].

Figure 4.9 shows specific dissipation sensitivity to coolant inlet temperature. The percent error indicates the change in dissipation relative to results at coolant inlet temperature at 100 °C. Errors are less than ± 1.0% under laminar flow and less than ± 2.0% for transitional and turbulent flows for temperature variation within 10 °C [17].

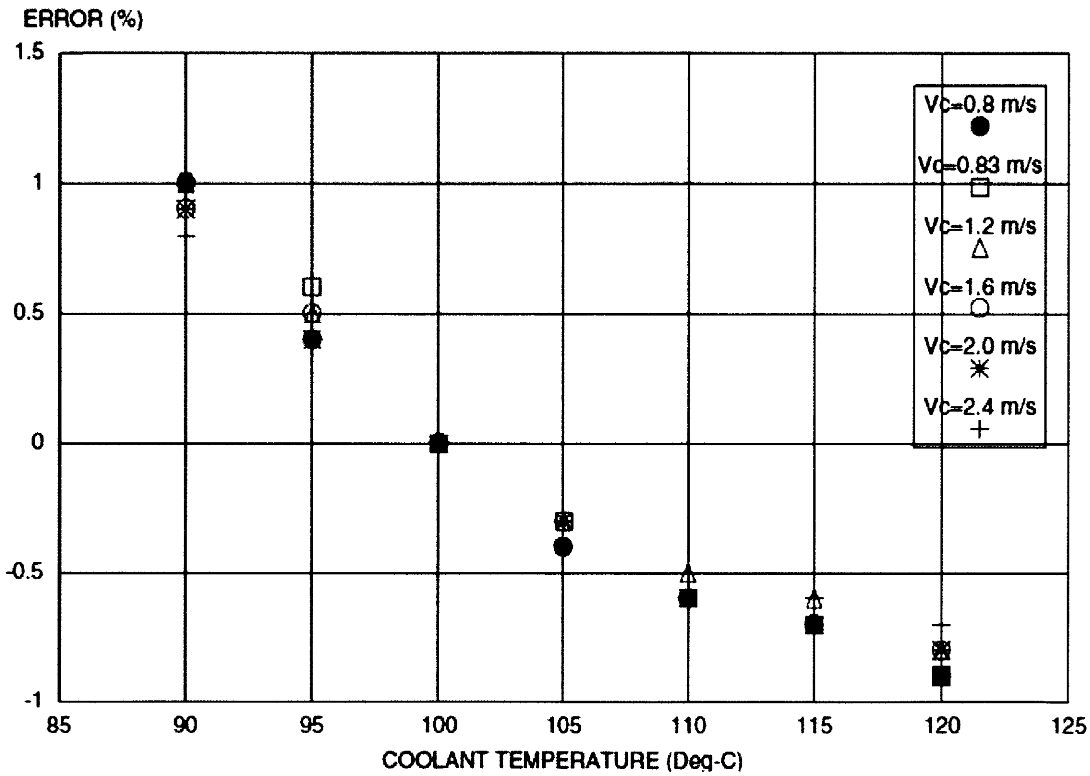

Figure 4.9 – Fuel Consumption Sensitivity to Coolant Temperature [17]

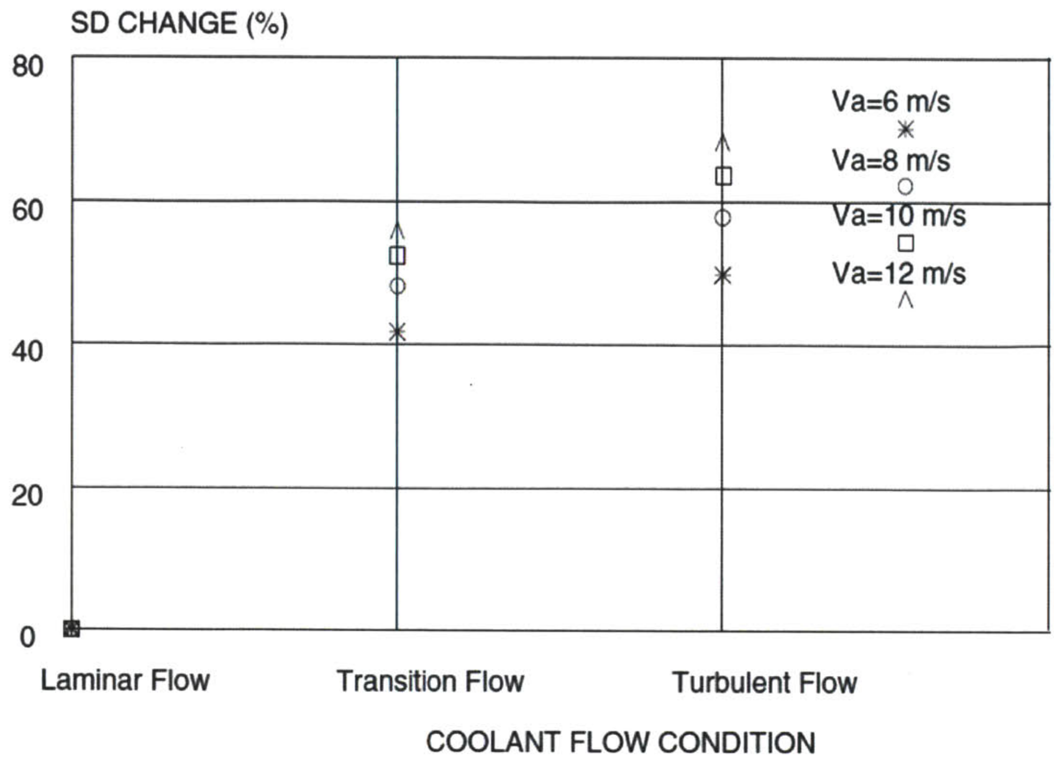

Figure 4.10 – Specific Dissipation Sensitivity to Coolant Flow Rate [17]

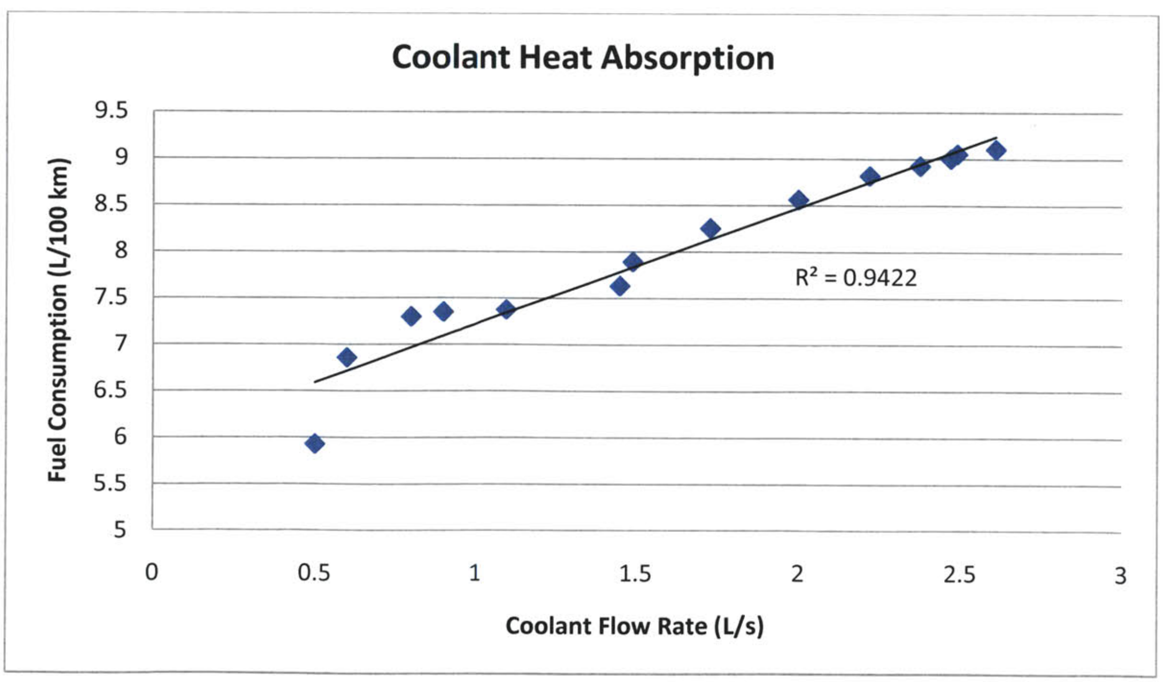

Figure 4.11 – Correlation between Fuel Consumption and Coolant Flow Rate

Figures 4.10 and 4.11 depict specific dissipation sensitivity to coolant flow rate. The percent error indicates the change in dissipation relative to results at coolant flow rate of 1 m/s. Figure 4.10 indicates that, at 1.0 L/s, a 1 % flow rate variation will cause about ± 0.6 % specific dissipation variation [17].

Figure 4.11 reveals a strong correlation (R^2 = 0.942) between coolant flow rate and fuel consumption by the cooling system. From the slope of the line, it is shown that a 1.0 ± 0.1 L/s increase in coolant flow rate results in a 1.26 ± 0.05 L/100 km increase in fuel consumption by the cooling system during engine operation.

4.2.2. Engine

The study used for engine analysis [25] tests a Ford Orion gasoline engine car. The vehicle is instrumented with 28 Type K thermocouples, which are connected to a Daqbook/200 data logger. Exhaust emissions are measured using sampling bags, which are use to calculated fuel consumption in g/kWh. This is converted to L/100 km using

$$FC = 80\frac{kWh}{100\,km} \times \frac{7.3\times10^{-4}\ L}{g\ gasoline} \times \left[\frac{g}{kWh}\right] \tag{8}$$

Figure 4.12 displays a strong correlation between fuel consumption and ambient temperature (R^2 = 0.825). The slope of the line indicates that a 1.0 ± 0.5 °C change in ambient temperature results in a 0.05 ± 0.01 L/100 km decrease in fuel consumption.

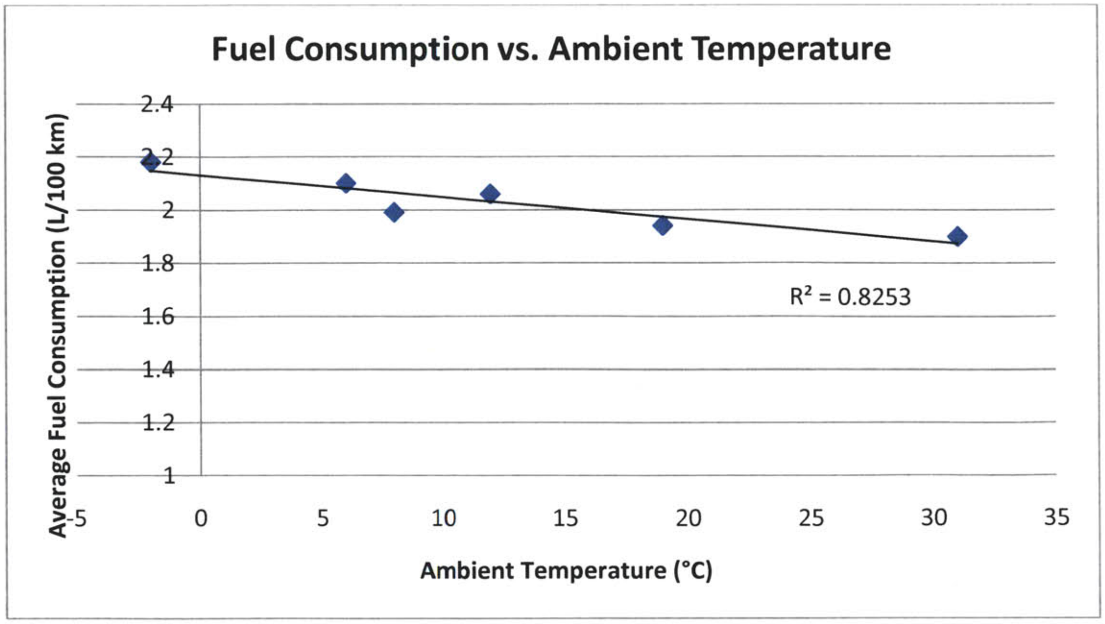

Figure 4.12 – Correlation between Fuel Consumption and Ambient Temperature for Engine

4.2.3. Lubricants

Data from five technical papers are used to understand the relationship between HTHS viscosity and fuel consumption [26-30]. Each study isolates the engine from the rest of the automobile to directly study the effect of changing oil viscosity. Most studies do a comparison between viscosity and specific fuel consumption. It is converted to fuel consumption (FC) using

$$FC = 80\frac{kWh}{100\,km} \times \frac{7.3\times10^{-4}\ L}{g\ gasoline} \times SFC \tag{9}$$

where 80 kWh/100 km is the average energy consumption of a midsize passenger car [45], 7.3 x 10^{-4} L/g is the density of gasoline, and specific fuel consumption (SFC) is measured in units of g/kWh.

Gasoline or diesel engines are used to make a comparison between different engines, the efficiency of each engine at an engine speed of 4500 RPM is used – 19% for gasoline engines, 20% for diesel engines [7]. Equation (10) is used to convert fuel consumption of a diesel engine to that of a gasoline engine.

$$FC_{GE} = \frac{\eta_{DE}}{\eta_{GE}} \times FC_{DE} \tag{10}$$

A comparison between provided data showed that all technical papers resulted in fuel consumptions of the same order of magnitude. Figure 4.13 shows the results from a study [27] on the correlation between fuel consumption and viscosity. The study uses an isolated Euro 2 diesel engine at various engine speeds and loads to simulate different driving conditions – extra-urban, urban, regional and highway driving. Seven different oil lubricants are use for this study, with none having friction additives (Table 4.1).

Table 4.1 – Oil Lubricant Properties [27]

Lubricant	SAE – class	Viscosity at 100 °C [cSt]	HTHS viscosity [cPs]	CCS at -25 °C [cPs]	Sulphur content [ppm]
A	15W-40	14.70	4.26	6680*	7735
B	10W-30	11.62	3.56	6720	6092
C	10W-30	9.95	3.10	6160	5959
D	10W-30	11.16	3.46	4680	1438
E	10W-30	9.91	3.15	4630	1372
F	10W-40	14.52	4.25	6170	1508
G	10W-40	14.40	3.91	6200	7742

*CCS at -20 °C

Figure 4.13 reveals a strong correlation between HTHS viscosity and fuel consumption, with a coefficient of determination equal to 0.905. The data is found to be statistically significant at a 95% confidence interval, and from its slope, indicates that a 1.0 ± 0.1 cP increase in HTHS viscosity results in a 0.18 ± 0.02 L/100 km increase in fuel consumption.

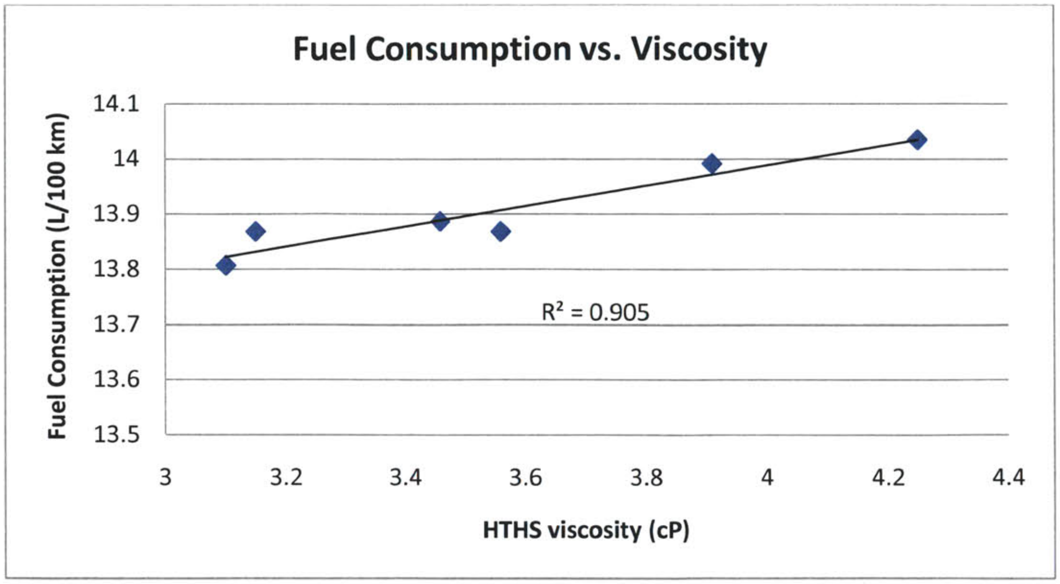

Figure 4.13 – Correlation between Fuel Consumption and HTHS Viscosity for Lubricants

4.2.4. Tires

An exact number for the effect of ambient temperature on fuel consumption is not found as different tires perform optimally at different temperatures due to the material properties of the tire walls. The behavior of changing ambient temperature, however, is quantifiable and referenced as every 1 °C increase in temperature resulting in a 0.5% - 1% decrease in fuel consumption for all passenger vehicles [46]. Using this as a model and assuming an average fuel consumption drop of 0.75%, Figure 4.14 is created to depict that relationship.

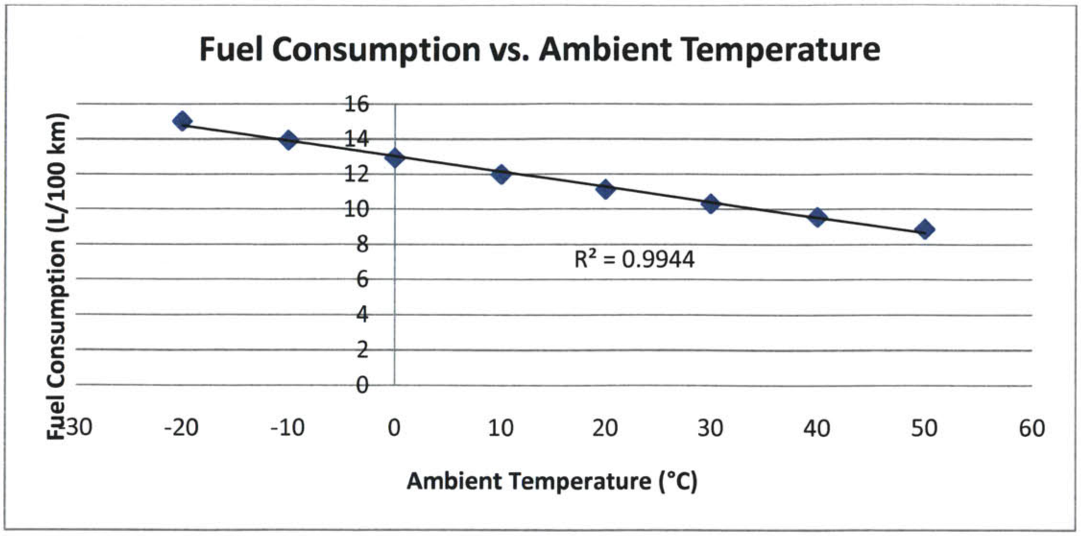

Figure 4.14 – Correlation between Fuel Consumption and Ambient Temperature for Tires

Figure 4.14 shows a strong correlation between tire pressure and fuel consumption, with a coefficient of determination equal to 0.994, which is expected given that the data is hypothetical. The data is found to be statistically significant at a 95% confidence interval.

The slope of the line changes depending on the starting fuel consumption, making it easier to quantify in terms of percentage drop. For this study, that value is chosen to be 10.7 L/100 km at 25 °C as the average fuel economy for a midsize passenger vehicle is 22 mpg [47], which is converted to L/100 km using equation (11); 25 °C is chosen arbitrarily as the corresponding temperature.

$$FC = \frac{1}{MPG} \cdot \frac{62.14\ mi}{100\ km} \cdot \frac{3.7854\ L}{1\ gal} \tag{11}$$

Figure 4.14 shows that low ambient temperature has a much larger effect on fuel consumption than high temperatures. Although high temperature results in lower fuel consumption, a temperature increase from -20 to 10 °C results in a larger change in fuel consumption than a temperature increase from 10 to 30 °C.

The effect of the coefficient of rolling resistance is evaluated in several technical papers. To investigate this relationship, data from one study is used [32]. This study is chosen as it analyzes the effect of a tire's coefficient of rolling resistance on midsized passenger vehicles with gasoline engines at a constant temperature of 25 °C.

Rolling resistance coefficient is analyzed on two Euro 4 engine vehicles. The coefficient of rolling resistance is measured using a loading test for each tire prior to experiment in order to validate the measurements reported by the tire companies. An error of ± 0.1 kg/t is calculated for each.

Figure 4.15 shows a strong correlation between the coefficient of rolling resistance and fuel consumption, with a coefficient of determination equal to 0.997. The data is found to be statistically significant at a 95% confidence interval, and from its slope, indicated that a 1.0 ± 0.1 kg/t increase in a tire's coefficient of rolling resistance resulted in a 0.13 ± 0.05 L/100 km increase in fuel consumption.

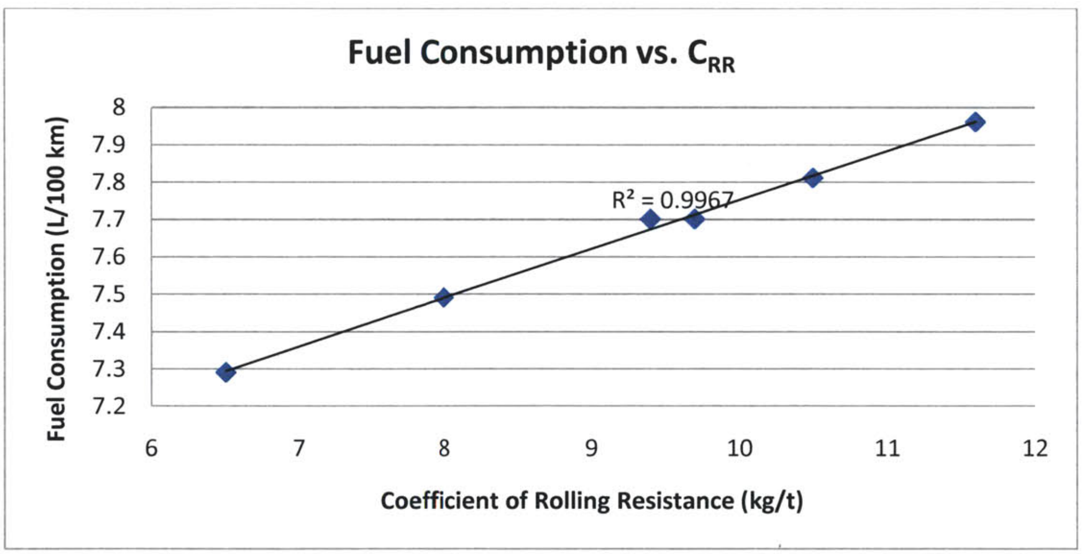

Figure 4.15 – Correlation between Fuel Consumption and Tire Coefficient of Rolling Resistance

Similar to rolling resistance, there is no exact number for the effect of tire pressure on fuel consumption as different tires perform optimally at different pressures due to the material properties of the tire walls and the vehicle load. The effect of tire pressure, however, is quantifiable and referenced as every 1 psi increase in tire pressure resulting in a 0.03% decrease in fuel consumption for all passenger vehicles [46]. Using this as a reference, Figure 4.16 is created to depict that relationship. Air pressure is converted from psi to kPa using Table 2.1.

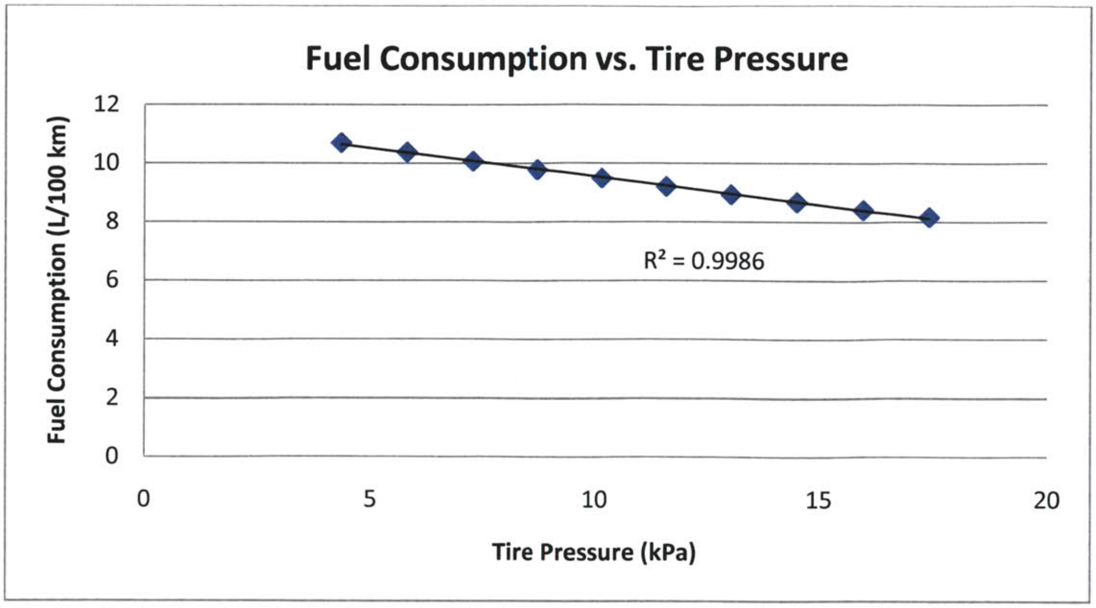

Figure 4.16 – Correlation between Fuel Consumption and Tire Pressure

Figure 4.16 shows a strong correlation between tire pressure and fuel consumption, with a coefficient of determination equal to 0.999, which is expected given that the data is hypothetical. The data is found to be statistically significant at a 95% confidence interval.

The slope of the line changes depending on the starting fuel consumption, making it easier to quantify in terms of percentage drop. For this study, that value is chosen to be 10.7 L/100 km at 4.35 kPa (30 psi) as the average fuel economy for a midsize passenger vehicle is 22 mpg [46], converted to L/100 km using equation (11) and 30 psi is chosen as a typical tire pressure.

Figure 4.16 shows that low tire pressure has a much larger effect on fuel consumption than higher pressure. Although high pressure results in lower fuel consumption, a pressure increase from 4 to 5 kPa results in a larger change in fuel consumption than a pressure increase from 14 to 15 kPa.

4.3. Summary of Findings

Table 4.2 provides a summary of the key relationships determined in this study.

Table 4.2 – Summary of Linear Relationships

Vehicle Component	Fuel Consumption (L/100 KM)	Significant?	Rank
Air Conditioning			
• Ambient Temperature (+1 °C)	0.05 ± 0.01	Yes	4
• Relative Humidity (+1 %)	No correlation found	No	---
Alternator			
• Ambient Temperature (+1 °C)	$3 \times 10^{-5} \pm 5 \times 10^{-6}$	No	---
• Current Output (+1 A)	$0.002 \pm 5 \times 10^{-4}$	Yes	5
Coolant			
• Ambient Temperature (+1 °C)	No correlation found	No	---
• Coolant Temperature (+1 °C)	No correlation found	No	---
• Coolant Flow Rate (+1 L/s)	1.26 ± 0.05	Yes	1
Engine			
• Ambient Temperature (+1 °C)	-0.05 ± 0.01	Yes	4
Lubricants			
• Viscosity (+1 cP)	0.18 ± 0.02	Yes	2
Tires			
• Ambient Temperature (+1 °C)	-0.09 ± 0.01*	Yes	**
• Coefficient of Rolling Resistance (+1 kg/t)	0.13 ± 0.05	Yes	3
• Tire Pressure (+1 kPa)	0.19 ± 0.07*	Yes	**

**Values calculated for average fuel economy of U.S. midsized passenger car, 22-mpg, at 30 psi*
***Unable to rank. Dependent on vehicle load and tires.*

The coolant has the strongest effect on vehicle fuel consumption, followed by lubricant, rolling resistance, air conditioning and the alternator. Coolant flow rate is the strongest contributing factor to fuel consumption, and alternator current output is the weakest of the factors (Figure 4.17).

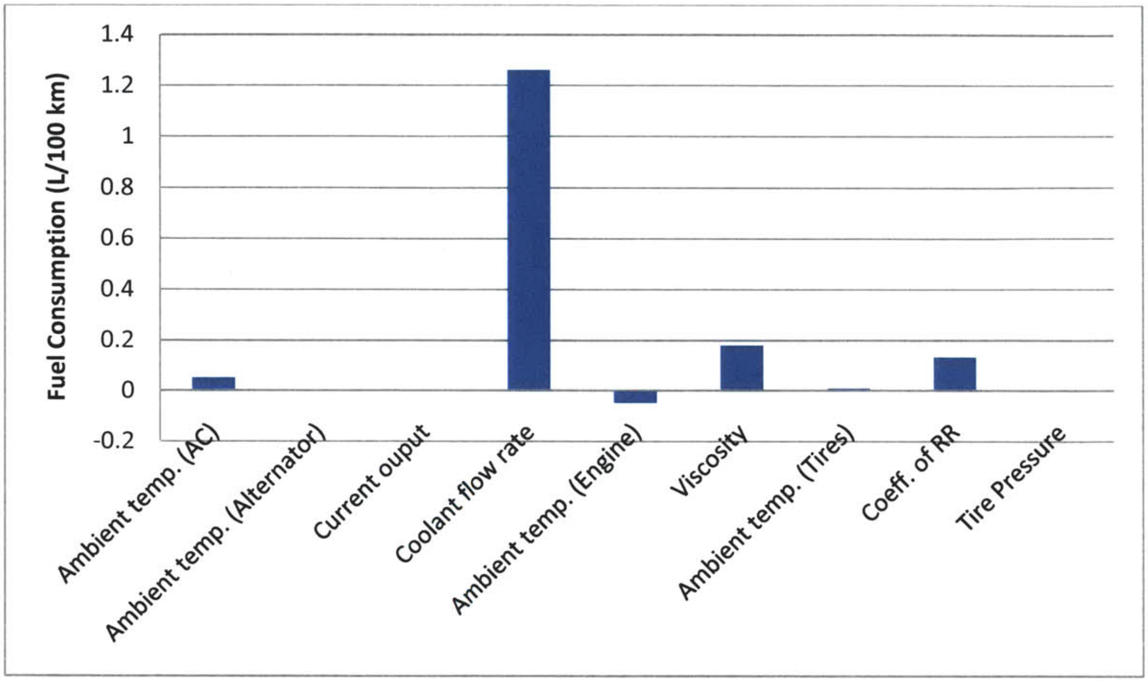

Figure 2.17 - Fuel Consumption due to a unit change in External Factor

Although ambient temperature in magnitude is not the strongest factor for any of the components, it has a direct effect on all components, excluding lubricants. It is possible that, when considering all components operating in conjunction, ambient temperature potentially has an overall greater effect on vehicle fuel consumption. From the literature review, it was found that ambient temperature is cited as having direct impact on fuel consumption on all components except lubricants.

5. Conclusions

This study investigated the key components responsible for vehicle fuel consumption and the external factors that influence fuel consumption for each component. A thorough literature review of selected technical papers identified key factors that are consistently found to impact individual vehicle component fuel consumption. Relationships between external factors and fuel consumption for each component are identified through linear regression models run on data available in the literature.

Results from the analysis indicated that coolant, lubricants, rolling resistance, air conditioning and alternator significantly contributed to vehicle fuel consumption. Coolant flow rate had the greatest impact on vehicle fuel consumption (1.26 ± 0.05 L/100 km) and alternator current output had the smallest impact (0.002 ± 5 x 10^{-4} L/100 km). Ambient temperature has an effect on nearly all vehicle components, giving the implication that it has an overall larger effect on vehicle fuel consumption and it is the strongest factor.

There are several limitations to take into consideration when looking at the results of this study. Only a handful number of accessible technical papers exist that have researched the contribution of fuel consumption of these components, providing a limitation in the scope of this literature review.

Attempts are made to minimize uncertainty by providing limitations to certain variables. The engines analyzed are limited to only gasoline, driving cycle is restricted to highway or regional driving, and conversions were made in cases where there were deviations from this, such as studies using diesel engines. However, variation and restrictions exist within those limitations that could not be controlled. Not all gasoline engines have the same configuration, all regional and highway driving cycles are not the same, and conversions can only provide theoretical insight where empirical observations are needed.

Additionally, although all results for this study proved to be statistically significant with 95% confidence interval, except for the relationship between relative humidity and fuel consumption, the inability to manipulate experimental systems which yielded the data used in this study augments the uncertainty of the results. A possible solution to experimental discrepancies in the literature would be to perform controlled empirical investigations. The ability to control certain variables – driving cycle, engine configuration and type, engine speed, etc. – will prove invaluable in further understanding the impact of individual components and external factors on vehicle contribution.

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